Site-Dependent Spectra Derived from Ground Motion Records in Turkey

Erol Kalkan,[a)] S.M.EERI, and Polat Gülkan,[b)] M.EERI

The current spectral shapes in the *Turkish Seismic Code* (*TSC*) are based on broadly described geological conditions, ignoring fault distance or magnitude dependencies on spectral ordinates. To address this deficiency, a data set created from a suite of 112 strong ground motion records from 57 earthquakes that occurred between 1976 and 2003 has been used to develop horizontal attenuation relationships for Turkey. This way it is possible to construct hazard-consistent design spectra for any national seismic region. The results are compared with the site-dependent spectral shapes of the *Uniform Building Code* (*UBC*) and the current TSC. It is shown that corner periods are consistent with those of *UBC*. TSC yields wider constant spectral acceleration plateau. Design spectra in both of these documents are conservative if the ground motion library that we used in deriving the spectral shapes is taken as representative. The results of this study enable site-distance–magnitude-specific design spectra suitable as a tool both for deterministic (scenario earthquakes) and probabilistic seismic hazard assessments.
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INTRODUCTION

In 1999, two earthquakes occurred about three months apart on the North Anatolian Fault (NAF), and struck the Kocaeli and Düzce provinces in Turkey with magnitudes (M_W) 7.4 and 7.2, respectively. These earthquakes have once again emphasized the phenomenological influence of local geological conditions on levels of damage and resultant loss of life. In the aftermath of these events, most of their detrimental effects were concentrated in areas underlain by soft soil deposits. These concentrations of damage have accentuated the need to modify the current design provisions in Turkey to account better for the effects of local site conditions.

In general, achievement of adequate earthquake-resistant design of structures and consequent minimization of losses and damages from such devastating earthquakes require a reliable ground motion prediction either through the use of special earthquake maps and seismic provisions or, more specifically, from site-specific investigations. However, there is rarely a sufficient number of ground-motion recordings near a site to allow a direct empirical confirmation of motions expected for a design earthquake. For that reason, it is essential to develop design spectra expressed in the form of curves for estimating ground motions in terms of magnitude, distance, and local site conditions. This in turn makes design spectra the pivotal instrument for both site-specific design and

[a)] University of California Davis, Department of Civil and Environmental Engineering, Davis, CA 95616
[b)] Middle East Technical University, Department of Civil Engineering, Ankara, 06531, Turkey

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regional earthquake hazard mapping. With the increasing number of records now available in Turkey, it appears possible to explore the relationship between the general characteristics of spectral shapes derived from strong ground motion records and the parameters affecting them. These relations and the values of their predictor parameters were developed through an extensive analysis of strong ground motion data and its relevant information as the extension of our previous study, related to attenuation modeling of horizontal and vertical ground motion in Turkey (Gülkan and Kalkan 2002, Kalkan and Gülkan 2004a). The updated database, analyses, and the results of the empirical study complementing this work are summarized in the remaining sections of this article. With all this information, the present study provides a general framework for developing estimates of site-dependent design spectra based on specific parameters characterizing the earthquake magnitude, geology of the site, and the distance between source and site with associated measures of uncertainty. This study also includes comparisons between design spectra developed elsewhere and those tailored for Turkey, and examines their differences. It is anticipated that future revisions of the seismic code will consider the spectrum shapes described herein. The results of this article are a first step toward developing vernacular spectral shapes for earthquake engineering applications in Turkey.

DATABASE

A data set from 223 horizontal components from 112 strong ground motion records of 57 earthquakes that occurred between 1976 and 2003 in Turkey has been created as the expanded and updated version of the previously compiled database by Gülkan and Kalkan (2002). The former data set consisted of 47 horizontal components of 19 earthquakes between 1976 and 1999, and in this new rendition several post-1999 events have been added. The current database includes data recorded within 250 km of the causative fault from earthquakes in the magnitude range of 4.0 to 7.4. Its latest entry is the Buldan-Denizli earthquake of 26 July 2003. All of the earthquakes occurred in the shallow crustal tectonic environment of Turkey. The list of these events and the number of recordings for each of their site categories are presented in Table 1. A more comprehensive description of the strong motion database is presented in Table A1 in the Appendix, where station names and their abbreviations have been reproduced exactly as they were originally reported so that independent checks may be made. The epicenters of earthquakes and locations of the recording stations are marked on an active faulting map of Turkey, and exhibited in Figure 1. That figure is a reminder that the records used are mostly representative for the active tectonic environment of Turkey during the last quarter century.

In the database, earthquake size was characterized by moment magnitude M_W (Hanks and Kanamori 1979). When original magnitudes were listed in other scales, conversion was done according to Wells and Coppersmith (1994) and Kramer (1996). The magnitudes were restricted to about $M_W \geqslant 4.0$ to limit the analysis to more reliably recorded events. Several parameters in the former data set, including the closest distance, magnitude, and site geology, were revised based on the collection of supplemental information after 1999. This revision was considered necessary since the data comes from a variety of sources of different accuracy and reliability. The sources of information are also referenced in Table A1 in the Appendix for each of their corresponding data points.

Table 1. Earthquakes used in the analysis

Event No	Date (dd.mm.yy)	Event	Faulting Type *	M_W	Depth (km) *	Epicenter Coordinates *	Number of Recordings Rock	Soil	Soft Soil
1	19.08.1976	DENİZLİ	Normal	5.3	20.0	37.7100N - 29.0000E		1	
2	05.10.1977	ÇERKEŞ	Strike-Slip	5.4	10.0	41.0200N - 33.5700E			1
3	16.12.1977	İZMİR	Normal	5.5	24.0	38.4100N - 27.1900E			1
4	11.04.1979	MURADİYE	Strike-Slip	4.9	44.0	39.1200N - 43.9100E	1		
5	28.05.1979	BUCAK	Normal	5.8	111.0	36.4600N - 31.7200E	1		
6	18.07.1979	DURSUNBEY	Strike-Slip	5.3	7.0	39.6600N - 28.6500E	1		
7	30.06.1981	HATAY	Strike-Slip	4.7	63.0	36.1700N - 35.8900E		1	
8	05.07.1983	BİGA	Reverse	6.1	7.0	40.3300N - 27.2100E	2		1
9	30.10.1983	HORASAN-NARMAN	Strike-Slip	6.5	16.0	40.3500N - 42.1800E			2
10	29.03.1984	BALİKESİR	Strike-Slip	4.5	0.0	39.6400N - 27.8700E			1
11	17.06.1984	FOÇA	Normal	5.0	0.0	38.8700N - 25.6800E	1		
12	12.08.1985	KİĞI	Strike-Slip	4.9	29.0	39.9500N - 39.7700E		1	
13	06.12.1985	KÖYCEĞİZ	Strike-Slip	4.6	0.0	36.9700N - 28.8500E			1
14	05.05.1986	MALATYA	Strike-Slip	6.0	4.0	38.0200N - 37.7900E	1		
15	06.06.1986	SÜRGÜ (MALATYA)	Strike-Slip	6.0	11.0	38.0100N - 37.9100E	1	1	
16	20.04.1988	MURADİYE	Strike-Slip	5.0	55.0	39.1100N - 44.1200E	1		
17	12.02.1991	İSTANBUL	Strike-Slip	4.8	10.0	40.8000N - 28.8200E	1		
18	13.03.1992	ERZİNCAN	Strike-Slip	6.9	27.0	39.7200N - 39.6300E		1	1
19	06.11.1992	SİVRİHİSAR	Normal	6.1	17.0	38.1600N - 26.9900E			1
20	03.01.1994	ISLAHİYE	Strike-Slip	5.0	26.0	37.0000N - 35.8400E		1	
21	24.05.1994	GİRİT	Normal	5.0	17.0	38.6600N - 26.5400E	1		
22	13.11.1994	KÖYCEĞİZ	Strike-Slip	5.2	10.0	36.9700N - 28.8090E			1
23	29.01.1995	TERCAN	Strike-Slip	4.8	31.0	39.9008N - 40.9900E		1	
24	26.02.1995	VAN	Strike-Slip	4.7	N/A	38.6000N - 43.3300E			1
25	01.10.1995	DİNAR	Normal	6.4	5.0	38.1100N - 30.0500E		1	1
26	02.04.1996	KUŞADASI	Normal	4.9	33.0	37.7800N - 26.6400E			1
27	14.08.1996	MERZİFON	Strike-Slip	5.4	10.0	40.7900N - 35.2300E			1
28	21.01.1997	BULDAN	Normal	4.8	9.0	38.1200N - 28.9200E		1	
29	22.01.1997	HATAY	Strike-Slip	5.5	23.0	36.1400N - 36.1200E		2	
30	28.02.1997	MERZİFON	Strike-Slip	4.7	5.0	40.6800N - 35.3000E			1
31	03.11.1997	MALAZGİRT	Strike-Slip	4.9	N/A	38.7600N - 42.4000E			1
32	04.04.1998	DINAR	Normal	4.6	7.0	38.1400N - 30.0400E		1	1
33	27.06.1998	ADANA-CEYHAN	Strike-Slip	6.3	18.0	36.8500N - 35.5500E	1	3	2
34	09.07.1998	BORNOVA	Normal	5.1	21.0	38.0800N - 26.6800E			1
35	17.08.1999	KOCAELİ	Strike-Slip	7.4	18.0	40.7000N - 29.9100E	8	9	9
36	11.11.1999	SAPANCA-ADAPAZARI	Strike-Slip	5.7	8.9	40.8100N - 30.2000E		1	
37	12.11.1999	DÜZCE	Strike-Slip	7.2	10.0	40.7400N - 31.2100E	3	5	4
38	06.06.2000	ÇANKIRI-ORTA	Strike-Slip	6.1	10.0	40.7200N - 32.8700E			1
39	23.08.2000	HENDEK-AKYAZI	Strike-Slip	5.1	15.3	40.6800N - 30.7100E		2	2
40	04.10.2000	DENİZLİ	Normal	4.7	8.4	37.9100N - 29.0400E		1	
41	15.11.2000	TATVAN-VAN	Strike-Slip	5.5	10.0	36.9300N - 44.5100E			1
42	10.07.2001	ERZURUM-PASİNLER	Strike-Slip	5.4	5.0	39.8273N - 41.6200E			1
43	26.08.2001	YIĞILCA-DÜZCE	Strike-Slip	5.4	7.8	40.9455N - 31.5728E		1	
44	02.12.2001	VAN	Strike-Slip	4.5	5.0	38.6170N - 43.2940E			1
45	03.02.2002	SULTANDAĞI-ÇAY	Reverse	6.5	5.0	38.5733N - 31.2715E		1	1
46	03.04.2002	BURDUR	Strike-Slip	4.2	5.0	37.8128N - 30.2572E		1	
47	14.12.2002	ANDIRIN-K. MARAŞ	Strike-Slip	4.8	13.6	37.4720N - 36.2210E		1	
48	10.03.2003	AKYAZI	N/A	4.0	4.4	40.7283N - 30.5900E			1
49	10.04.2003	URLA-IZMIR	N/A	5.8	15.8	38.2568N - 26.8345E			1
50	01.05.2003	BINGOL	Strike-Slip	6.4	6.0	38.9400N - 40.5100E			1
51	21.05.2003	DUZCE	N/A	4.7	7.7	40.8700N - 30.9800E		1	
52	09.06.2003	BANDIRMA	N/A	4.0	14.7	40.2000N - 27.9700E		1	
53	06.07.2003	SAROS	N/A	5.3	9.1	40.4200N - 26.2100E			1
54	23.07.2003	BULDAN-DENIZLI-1	N/A	5.5	5.0	38.1718N - 28.8533E		1	1
55	26/07/2003	BULDAN-DENIZLI-2	N/A	5.3	5.0	38.1100N - 28.8800E			1
56	26/07/2003	BULDAN-DENIZLI-3	N/A	5.7	4.3	38.1100N - 28.8900E		1	1
57	26/07/2003	BULDAN-DENIZLI-4	N/A	5.2	8.5	38.1200N - 28.8400E			1
						Total	23	41	48

* Data source: Earthquake Research Department (ERD), General Directorate of Disaster Affairs
N/A: Information is not available

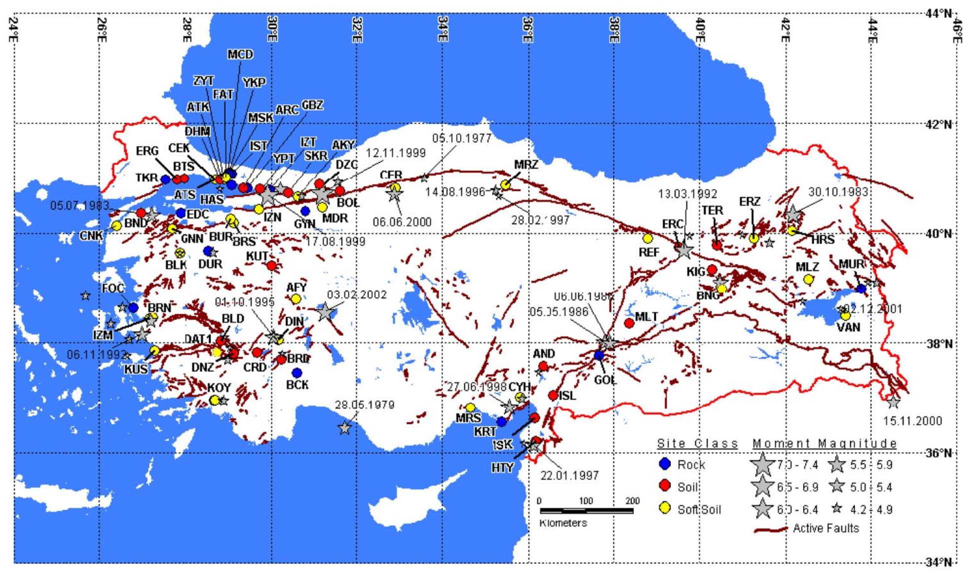

Figure 1. Epicenters of earthquakes and locations of strong motion recording stations on active fault map of Turkey.

Particularly, based on the information disseminated by USGS, PEER, and COSMOS, some correction and fine-tuning were done on the distance and local site condition parameters of the Kocaeli and Düzce events. Some of the station coordinates (e.g., Çerkeş Meteroloji İst.) were corrected by ERD (Earthquake Research Department of General Directorate of Disaster Affairs), causing distance revisions as large as 16.1 km in this new rendition.

As the source distance (r_{cl}), we adopted the closest horizontal distance (or Joyner and Boore distance) between the recording station and a point on the vertical projection of the rupture zone on the earth's surface (Boore et al. 1997). However, for some of the smaller events, rupture surfaces have not been defined clearly, so epicentral distances have been used instead. We believe that use of epicentral distance does not introduce significant bias because the dimensions of the rupture area for small earthquakes are usually much smaller than the distance to the recording stations. The distribution of the earthquakes in the data set in terms of PGA, magnitude, site geology, and source distance is demonstrated in Figure 2. Paucity of data from the small number of normal-faulting (14 recordings) and reverse-faulting earthquakes (5 recordings) in the data set did not permit us to treat the faulting mechanism as a parameter, as this would give undue weight to particular faulting categories. Therefore, normal, reverse, and strike-slip earthquakes were combined into a single faulting category. Until additional data becomes available this will constitute a constraint for the presented results in this article.

The data used in the analysis represents main shocks recorded mostly in small or medium-sized state-owned buildings up to three stories tall because the strong motion

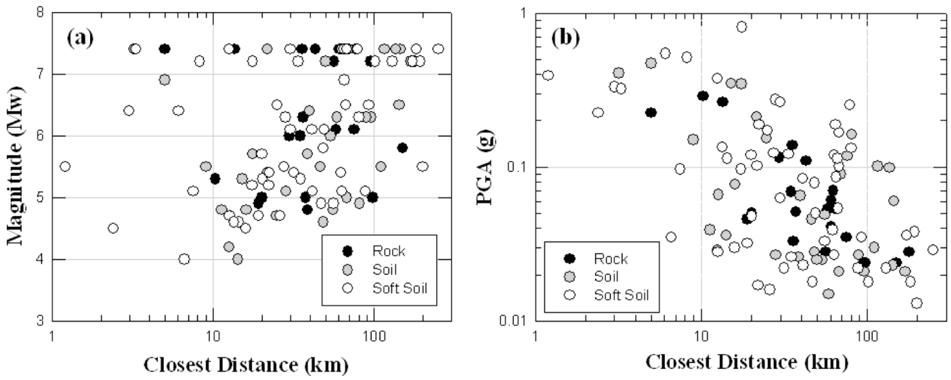

Figure 2. Distribution of records in the database in terms of (a) moment magnitude and closest distance, and (b) larger maximum horizontal acceleration of either component and closest distance.

stations in Turkey are colocated with institutional facilities for ease of access, phone hook-up, and security. This proximity contaminates the seismograms and causes modified acceleration records (e.g., Anderson et al. 2001). This is one of the unavoidable causes of uncertainties in our study, but there are other attributes that must be mentioned. The first is our omission of aftershock data. Most of these come from the two major 1999 events, and this small number of data was ignored due to the high nonlinear soil behavior observed in the close vicinity of their recording stations during the main shock of the Kocaeli earthquake (Safak et al. 2000, Bakir et al. 2002).

When we consider the effects of geological conditions on the ground motion and response spectra, the widely accepted method of reflecting these effects is to classify the recording stations according to the shear-wave velocity (V_S) profiles of their substrata in the upper 30 m (Boore et al. 1997). Recently, V_S measurements were conducted in several stations where records were made during the Kocaeli and Düzce events, and reported by Rathje et al. (2003). We have considered them in the updated database, yet for most stations in Turkey, reliable V_S values and detailed site descriptions are not available. For that reason we estimated the site classification for those stations roughly by analogy with information in similar geologic materials. The type of geologic material underlying each recording site was obtained in a number of ways: consultation with geologists at ERD, various local geologic maps, past earthquake reports, and geological references prepared for Turkey. Based on this collected qualitative data, we used a general classification of site geology that we could apply uniformly and that would be broadly applicable. We divided soil groups for recording stations in Turkey into three categories: rock (with average V_S=700 m/sec), soil (V_S=400 m/sec), and soft soil (V_S=200 m/sec). The correspondence between these values and more widely accepted soil categories is obviously tenuous. If ground motion estimates were to be done for a site in Turkey, then it should be assigned to the likeliest of these three velocities depending on the site geology reports.

ATTENUATION RELATIONSHIP

The attenuation equation in this study was developed in the same general form of the equation proposed by Boore et al. (1997). The general form of the ground motion parameter estimation equation is

$$\ln Y = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln(V_S/V_A) \qquad (1)$$

$$r = (r_{cl}^2 + h^2)^{1/2} \qquad (2)$$

where Y is the ground motion parameter (peak ground acceleration [PGA] or pseudo-spectral acceleration [PSA] in g), M is the (moment) magnitude; r_{cl} is the closest horizontal distance (or Joyner-Boore distance) from the station to a site of interest in km; V_S is the characteristic shear-wave velocity for the station in m/sec; and b_1, b_2, b_3, b_5, h, b_V, and V_A are the parameters to be determined. In the expression, h is a fictitious depth, and V_A is a fictitious velocity that is determined by regression. The coefficients in the median attenuation equation were determined by using one-stage nonlinear regression analysis. The larger value of the two horizontal components for each record was processed in the regression. This exercise was performed separately on PGA and absolute acceleration spectral ordinates individually. The spectral ordinates at 5 percent of critical damping were kept in the range of 0.1 to 2.0 sec (total of 46 periods) at the same period intervals as in the Caltech (1972) volumes. The form of Equation 1 ignores possible dependence of site shear-wave velocity on magnitude (or PGA). The coefficients for estimating the maximum horizontal component pseudo-acceleration response by Equation 1 are listed in Table 2. The resulting parameters can be used to produce attenuation relations that predict response spectra over the full range of magnitudes (M_W 4 to 7.5) and distances (r_{cl}) up to 250 km. The calculated attenuation curves for PGA for rock, soil, and soft soil sites are shown in Figure 3 for magnitude 5.0 and 7.0 earthquakes.

The results were processed to compute uncertainties for PGA and PSA at each spectral period. The standard deviation of the residuals ($\sigma_{\ln Y}$), expressing the random variability of ground motions, is in the range of 0.6 to 0.9 with respect to PGA and spectral accelerations. Residual plots of PGA estimation based on Equation 1 for the full data set as functions of magnitude and closest distance are presented in Figures 4 and 5 together with their linear best-fit relations. With respect to both magnitude and distance parameter, no significant trends are observed either for the full data set (Figures 4a and 5a) or for any of the site categories (Figures 4b and 5b). This may serve as evidence for magnitude and distance independency of the total residuals.

COMPARISON WITH RECENT ATTENUATION EQUATIONS

The attenuation relations given in Equation 1 with the coefficients in Table 2 were compared to those recently developed by Ambraseys et al. (1996), Boore et al. (1997), Campbell (1997), Sadigh et al. (1997), and finally Spudich et al. (1999). The equations in Boore et al. (1997) and Ambraseys et al. (1996) divide site classes into four groups according to their shear-wave velocities. The Campbell (1997) equations refer to alluvium (or firm soil), soft rock, and hard rock. Sadigh et al. (1997) and Spudich et al. (1999) state that their equations are applicable for rock and soil sites. Since our equation

Table 2. Coefficients for attenuation relation of mean horizontal PGA and 5-percent-damped PSA

	$\ln(Y)=b1+b2(M\text{-}6)+b3(M\text{-}6)^2+b5 \ln r+\mathbf{b}_V \ln(V_S/V_A)$ with $r=(r_{cl}^2+h^2)^{1/2}$							
Period (sec)	*b*1	*b*2	*b*3	*b*5	b_V	V_A	*h* (km)	$\sigma_{\ln Y}$
PGA	0.393	0.576	−0.107	−0.899	−0.200	1112	6.91	0.612
0.10	1.796	0.441	−0.087	−1.023	−0.054	1112	10.07	0.658
0.11	1.627	0.498	−0.086	−1.030	−0.051	1290	10.31	0.643
0.12	1.109	0.721	−0.233	−0.939	−0.215	1452	6.91	0.650
0.13	1.474	0.500	−0.127	−1.070	−0.300	1953	10.00	0.670
0.14	0.987	0.509	−0.114	−1.026	−0.500	1717	9.00	0.620
0.15	1.530	0.511	−0.127	−1.070	−0.300	1953	10.00	0.623
0.16	1.471	0.517	−0.125	−1.052	−298	1954	9.59	0.634
0.17	1.500	0.530	−0.115	−1.060	−0.297	1955	9.65	0.651
0.18	1.496	0.547	−0.115	−1.060	−0.301	1957	9.40	0.646
0.19	1.468	0.575	−0.108	−1.055	−0.302	1958	9.23	0.657
0.20	1.419	0.597	−0.097	−1.050	−0.303	1959	8.96	0.671
0.22	0.989	0.628	−0.118	−0.951	−0.301	1959	6.04	0.683
0.24	0.736	0.654	−0.113	−0.892	−0.302	1960	5.16	0.680
0.26	0.604	0.696	−0.109	−0.860	−0.305	1961	4.70	0.682
0.28	0.727	0.733	−0.127	−0.891	−0.303	1963	5.74	0.674
0.30	0.799	0.751	−0.148	−0.909	−0.297	1964	6.49	0.720
0.32	0.749	0.744	−0.161	−0.897	−0.300	1954	7.18	0.714
0.34	0.798	0.741	−0.154	−0.891	−0.266	1968	8.10	0.720
0.36	0.589	0.752	−0.143	−0.867	−0.300	2100	7.90	0.650
0.38	0.490	0.763	−0.138	−0.852	−0.300	2103	8.00	0.779
0.40	0.530	0.775	−0.147	−0.855	−0.264	2104	8.32	0.772
0.42	0.353	0.784	−0.150	−0.816	−0.267	2104	7.69	0.812
0.44	0.053	0.782	−0.132	−0.756	−0.268	2103	7.00	0.790
0.46	0.049	0.780	−0.157	−0.747	−0.290	2059	7.30	0.781
0.48	−0.170	0.796	−0.153	−0.704	−0.275	2060	6.32	0.789
0.50	−0.146	0.828	−0.161	−0.710	−0.274	2064	6.22	0.762
0.55	−0.306	0.866	−0.156	−0.702	−0.292	2071	5.81	0.808
0.60	−0.383	0.881	−0.179	−0.697	−0.303	2075	6.13	0.834
0.65	−0.491	0.896	−0.182	−0.696	−0.300	2100	5.80	0.845
0.70	−0.576	0.914	−0.190	−0.681	−0.301	2102	5.70	0.840
0.75	−0.648	0.933	−0.185	−0.676	−0.300	2104	5.90	0.828
0.80	−0.713	0.968	−0.183	−0.676	−0.301	2090	5.89	0.839
0.85	−0.567	0.786	−0.214	−0.695	−0.333	1432	6.27	0.825
0.90	−0.522	1.019	−0.225	−0.708	−0.313	1431	6.69	0.826
0.95	−0.610	1.050	−0.229	−0.697	−0.303	1431	6.89	0.841
1.00	−0.662	1.070	−0.250	−0.696	−0.305	1405	6.89	0.874
1.10	−1.330	1.089	−0.255	−0.684	−0.500	2103	7.00	0.851
1.20	−1.370	1.120	−0.267	−0.690	−0.498	2103	6.64	0.841
1.30	−1.474	1.155	−0.269	−0.696	−0.496	2103	6.00	0.856
1.40	−1.665	1.170	−0.258	−0.674	−0.500	2104	5.44	0.845
1.50	−1.790	1.183	−0.262	−0.665	−0.501	2104	5.57	0.840
1.60	−1.889	1.189	−0.265	−0.662	−0.503	2102	5.50	0.834
1.70	−1.968	1.200	−0.272	−0.664	−0.502	2101	5.30	0.828
1.80	−2.037	1.210	−0.284	−0.666	−0.505	2098	5.10	0.849
1.90	−1.970	1.210	−0.295	−0.675	−0.501	1713	5.00	0.855
2.00	−2.110	1.200	−0.300	−0.663	−0.499	1794	4.86	0.878

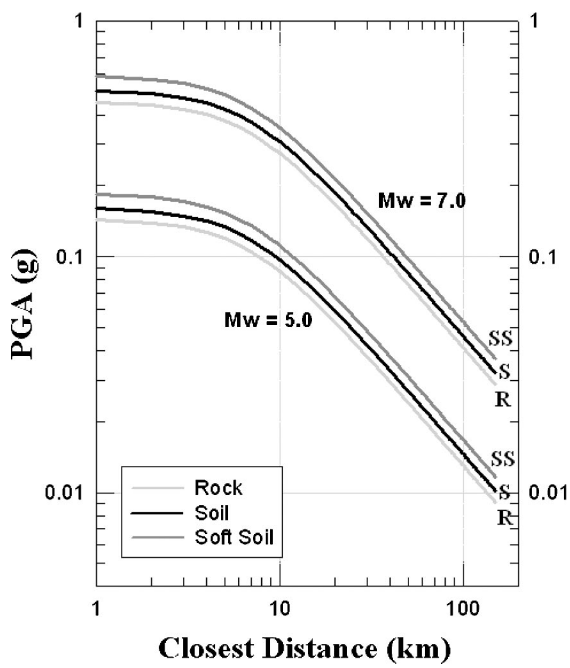

Figure 3. Curves of estimated PGA versus distance for magnitude 7.0 and 5.0 earthquakes at rock (R), soil (S), and soft soil (SS) site conditions, respectively.

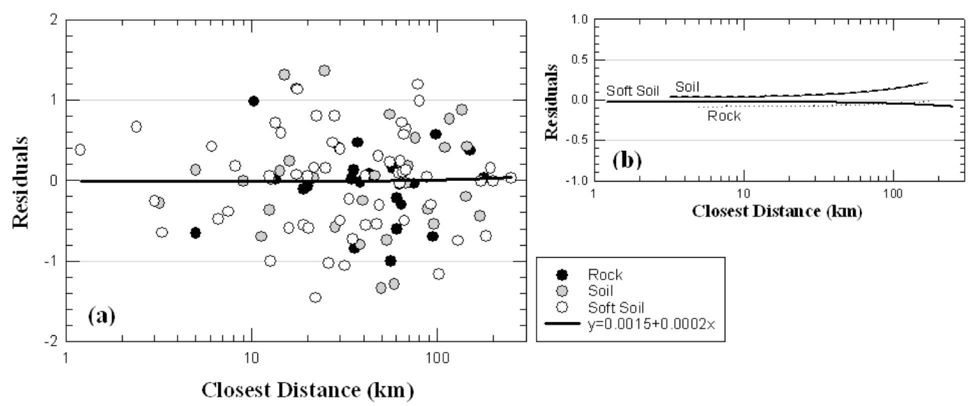

Figure 4. (a) Residuals of natural logarithm of PGA from Equation 1 as a function of closest distance; (b) linear regressions of residuals of natural logarithm of PGA on distance for three different site categories.

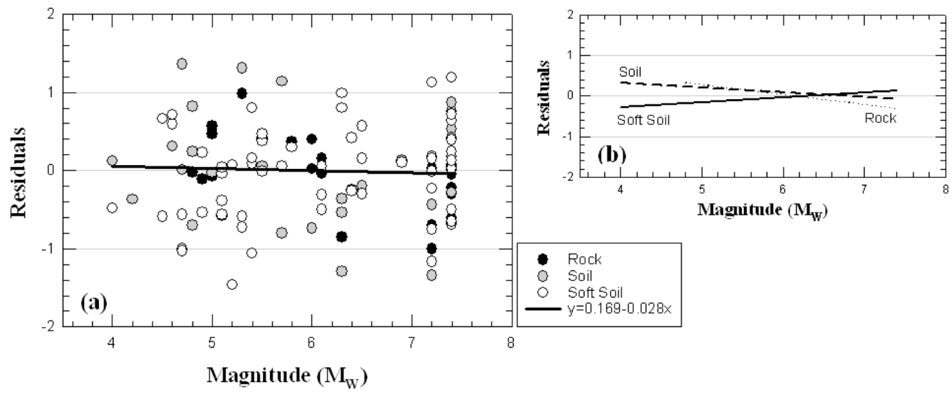

Figure 5. (a) Residuals of natural logarithm of PGA from Equation 1 as a function of magnitude; (b) linear regressions of residuals of natural logarithm of PGA on magnitude for three different site categories.

is similar to that of Boore et al. (1997), Figure 6 compares our results with that work for soft-soil site condition. Three-dimensional (3-D) attenuation surfaces shown in this figure give greater insight by freeing the magnitude term. These figures exhibit the higher estimates from Boore et al. (1997) at close distances and high magnitudes. There exists generally good agreement for distances greater than 10 km. The attenuation of PGA for $M_W=7.4$ earthquake for rock and soil sites is next compared with those recent models in Figure 7. The measured data points from the 1999 Kocaeli event are also marked on these figures to show how predictions agree with the observations. As it is inferred from the comparisons, ground motion amplitudes estimated by our attenuation model are gen-

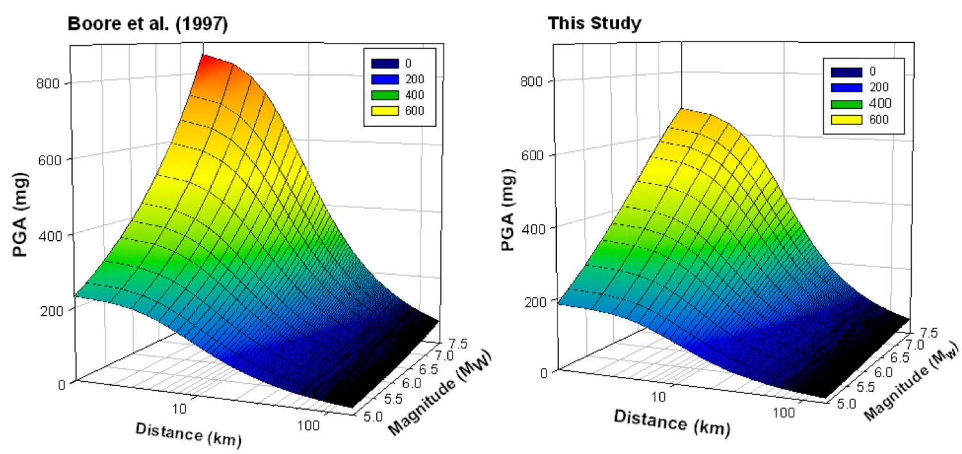

Figure 6. Comparison of our predictive model with that of Boore et al. (1997) on a 3-D plot for magnitude range of 5 to 7.5 and distance range of 0 to 150 km for soft-soil site conditions.

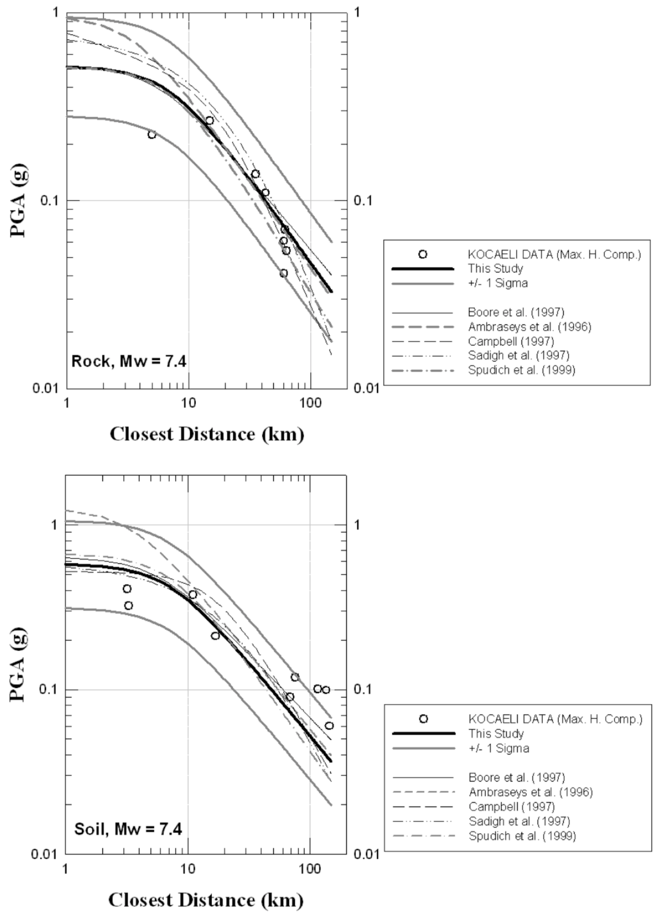

Figure 7. Curves of peak acceleration vs. distance for a magnitude 7.4 earthquake at rock and soil sites.

erally consistent with the measured data points. The best estimate curves in these figures correspond to mean values. Plus and minus sigma curves of our model are also drawn to show the 84-percentile prediction band. The peak acceleration estimate given here has a standard deviation of 0.612. Comparing the predictions of different models, we observe that our ground motion predictions are consistent with many recent models at both short and longer distances, but have generally greater deviation from the mean.

DEVELOPMENT OF SITE-DEPENDENT SPECTRA

Engineers and seismologists have long recognized the importance of response spectra as a means of characterizing ground motions produced by earthquakes and their effects on structures. Since the concept of a response spectrum was first introduced by Biot (1932, 1933) and extended by Housner (1941) to engineering applications, it has

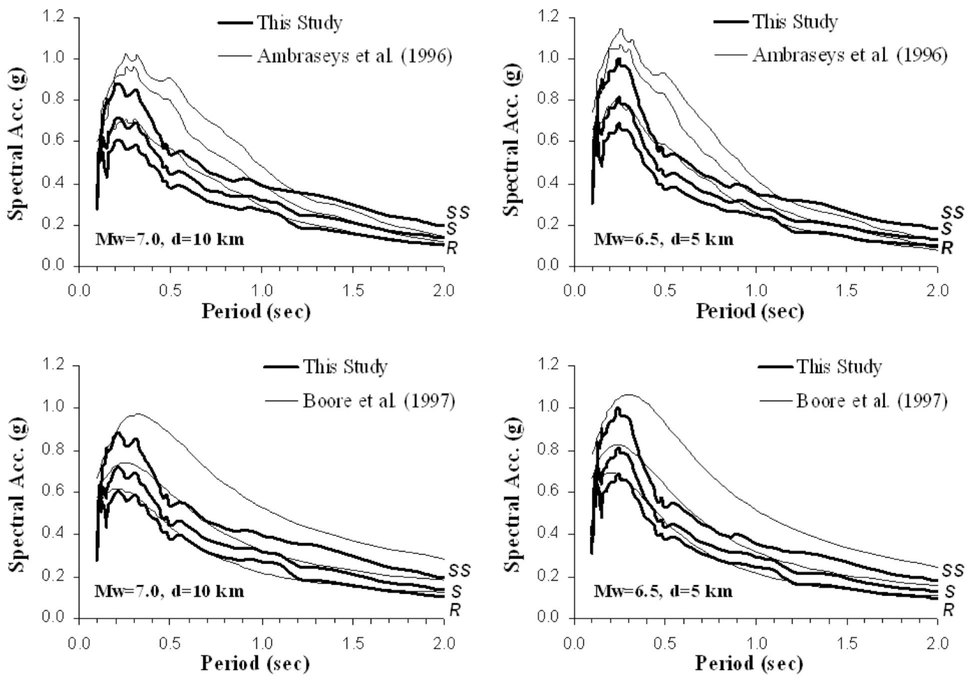

Figure 8. Expected mean spectra for rock, soil, and soft-soil site classes, for magnitude 6.5 and 7.0 earthquakes at a distance of 5 and 10 km (R=rock; S=soil; SS=soft soil).

been widely used for purposes of recognizing the significant characteristics of acceleration records and providing a simple way of evaluating the response of structures to strong ground shaking. In this study, to provide an indication of the differences in site-dependent spectra, response spectra for rock, soil, and soft-soil site classes were computed for different magnitude (M_W) and distance (r_{cl}) values by substituting them into Equation 1 with the coefficients listed in Table 2. This way, we have obtained more stable and reliable spectra than those developed solely based on PGA estimation. Typical examples of response spectra are compared with those obtained from predictive equations of Ambraseys et al. (1996) and Boore et al. (1997) in Figure 8 for M_W 6.5 and 7.0 events at distances of 5 and 10 km, respectively.

There exists a significant similarity in our estimated response curves and those chosen for comparison at low and high periods, yet our response curves fall below them at the mid-period range.

For practical applications, design spectra are presented as smooth curves or straight lines. Smoothing is justified because of the difficulties in determining the exact frequencies and mode shapes of structures during severe earthquakes when the behavior is most likely nonlinear. In this study, predicted horizontal response spectra were based on the

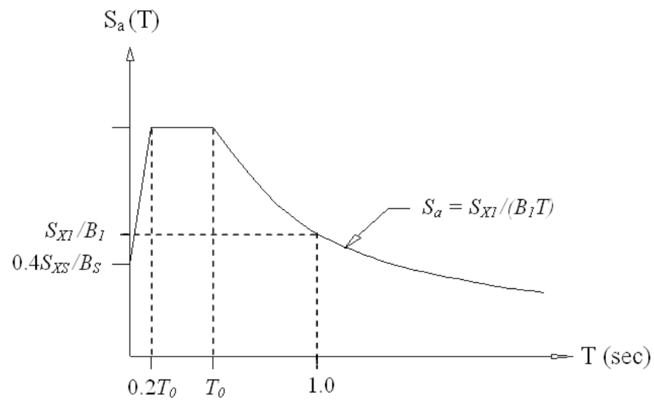

Figure 9. Construction of general response spectrum based on *FEMA-356*.

procedure prescribed in *FEMA-356* (ASCE 2000). Accordingly, each smoothed response spectrum was constructed by plotting the following three functions in the spectral acceleration vs. period domain as illustrated in Figure 9.

$$S_a=(S_{XS}/B_S)(0.4+3T/T_0) \quad \text{for} \ \ 0<T\leq 0.2T_0 \tag{3}$$

$$S_a=S_{XS}/B_S \quad \text{for} \ \ 0.2T_0<T\leq T_0 \tag{4}$$

$$S_a=(S_{X1}/(B_1T)) \quad \text{for} \ \ T>T_0 \tag{5}$$

where T_0 is given by Equation 6 and the values of B_S and B_1 in this equation are equal to unity for 5 percent of critical damping.

$$T_0=(S_{X1}/B_S)/(S_{XS}/B_1) \tag{6}$$

As in *FEMA-356*, the value of design spectral acceleration at short periods, S_{XS}, was taken as the response acceleration level obtained from the predicted spectrum at a period of 0.2 sec (based on Equation 1 and Table 2), with the exception that it should be taken as not less than 90 percent of the peak response acceleration at any period. To obtain a value for the design spectral response acceleration parameter S_{X1}, a curve of the form $S_a=S_{X1}/T$ was graphically overlain on the predicted spectrum such that at any period, the value of S_a obtained from the curve was not less than 90 percent of that which would be obtained directly from the predicted spectrum.

It is of interest to note that the value of S_{X1} is selected based on iteration, therefore one can select a range of values as long as it satisfies the condition given above. The decision for the value of S_{X1} (acceleration at 1 sec, since B is unity) was given here by considering both 50- and 84-percentile site-specific design spectra simultaneously. Therefore, the smooth spectra may seem to be more than the 50-percentile site-specific response spectrum at longer periods. As a consequence of such a methodology, the smooth spectra presented in Figure 10 were obtained. If we take a M_W 7.5 earthquake as a seismic design level for a site in Turkey, a general 5-percent-damped and normalized

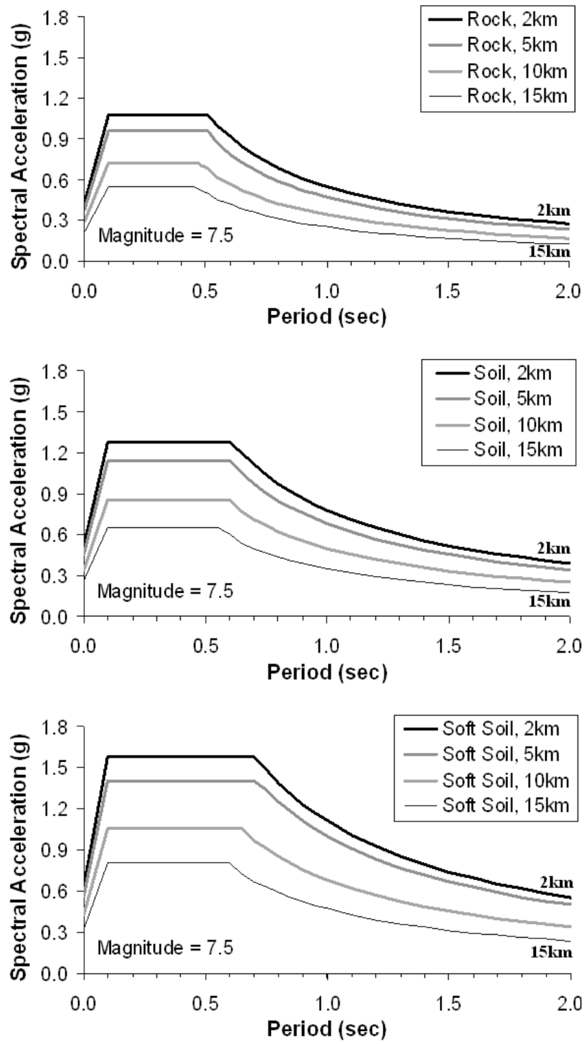

Figure 10. Smoothed spectra at 5 percent damping for a magnitude 7.5 earthquake for various distances at rock, soil, and soft soil sites.

horizontal design spectrum can be constructed based on the recommended corner periods given in Table 4 for various distance and geological conditions (described in Table 3) as in Figure 11.

Although the shear-wave velocities are taken as constant values during regression analyses, their corresponding values are presented here within intervals to better conform to current applications. Until better site characterizations become available, this lack of precision cannot be overcome. The procedure above for constructing the smooth spectrum does not cap the statistically derived curves in a "best" way. It is intended only that it should be used for design purposes, and be controlled only by S_{XS} and S_{X1}. The

Table 3. Generalized soil profile types

Soil Profile Name/Generic Description	Shear Wave Velocity, Vs (m/s)
Rock	>700
Soil	200 to 700
Soft Soil	<200

Table 4. Recommended corner periods (T_A,T_B) for the construction of design spectrum

	SOIL PROFILE TYPE					
	Rock		Soil		Soft Soil	
Distance*	T_A	T_B	T_A	T_B	T_A	T_B
<2 km	0.10	0.51	0.12	0.61	0.14	0.71
5 km	0.10	0.49	0.12	0.60	0.14	0.71
10 km	0.09	0.47	0.12	0.58	0.13	0.64
>15 km	0.09	0.45	0.11	0.54	0.12	0.59

* The distance will be taken as the minimum distance between the site and the area described by the vertical projection of the source on the surface (i.e., surface projection of fault plane).

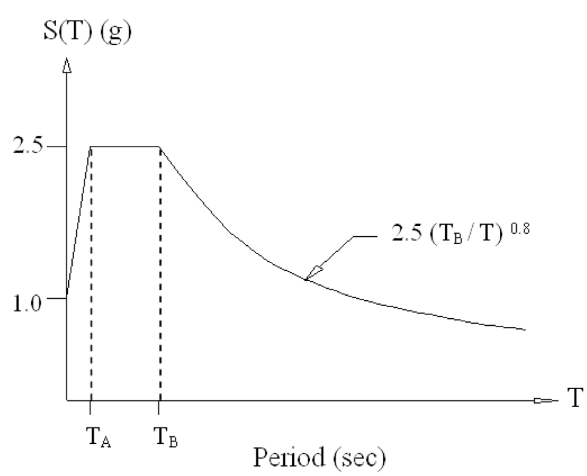

Figure 11. Construction of site-dependent design spectrum according to the TSC.

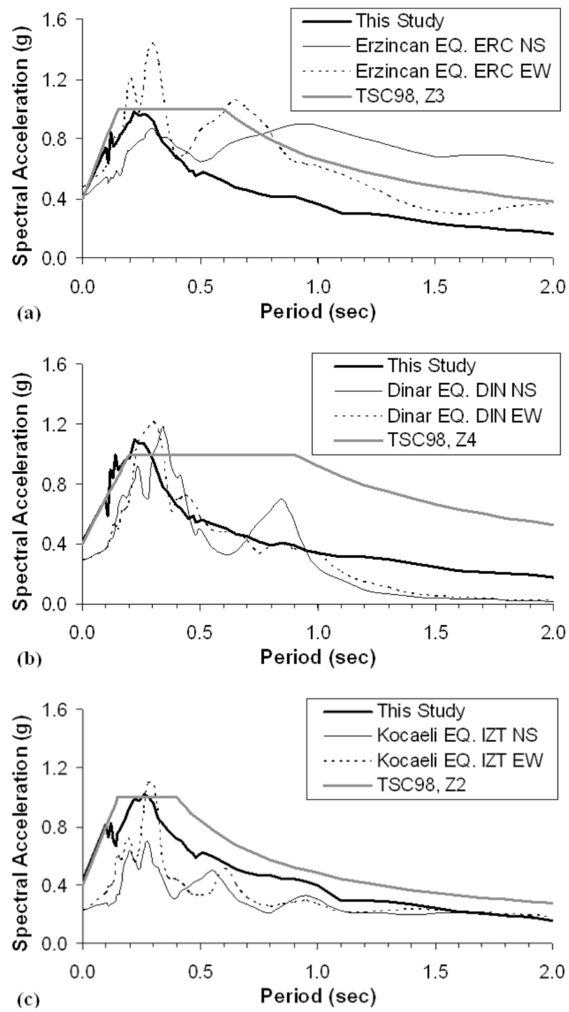

Figure 12. Comparison of mean predicted spectra from Equation 1 and Table 2 (for 5 percent damping) with computed response spectra for the NS and EW components of (a) Erzincan record, Erzincan earthquake of 1992, (M_W=6.9, Soil) and with *TSC* site class, Z3; (b) Dinar record, Dinar earthquake of 1995, (M_W=6.4, Soft soil) and with *TSC* site class, Z4; and (c) Izmit record, Kocaeli earthquake of 1999, (M_W=7.4, Rock) and with *TSC* site class, Z2.

comparisons of the site-dependent response spectra developed in this article with the attenuation formulas with the regulatory Turkish spectra and the *UBC* (ICBO 1997) are presented in the following sections.

COMPARISON WITH THE REGULATORY TURKISH DESIGN SPECTRA

The current *Turkish Seismic Code* (Ministry of Public Works and Settlement 1998) was last modified in 1998. We compare the spectra calculated for the strong motions

Table 5. *Turkish Seismic Code* soil and site classifications

Soil Group	Generic Description	Shear Wave Velocity (m/sec)	Site Class	Soil Group and Top Layer Thickness
(**A**)	1. Rock (Unweathered or Stiff)	>1000	**Z1**	Group (**A**) soils, h≤15 m
	2. Very dense sand, gravel	>700		Group (**B**) soils, h≤15 m
	3. Hard clay, silt clay	>700		
(**B**)	1. Soft rock (weathered)	700–1000	**Z2**	Group (**B**) soils, h>15 m
	2. Dense sand, gravel	400–700		Group (**C**) soils, h<15 m
	3. Very stiff clay, silty clay	300–700		
(**C**)	1. Highly weathered soft rock	400–700	**Z3**	Group (**C**) soils, h=15–50 m
	2. Medium dense sand and gravel	200–400		Group (**D**) soils, h≤10 m
	3. Stiff clay, silty clay	200–300		
(**D**)	1. Soft deep aluvial layers	<200	**Z4**	Group (**C**) soils, h>50 m
	2. Loose sand	<200		Group (**D**) soils, h>10 m
	3. Soft clay, silty clay	<200		

records of M_W 6.9 Erzincan (1992), M_W 6.4 Dinar (1995), and M_W 7.4 Kocaeli (1999) earthquakes with the regulatory spectra given in this reference and with our estimated response spectra (via Equation 1 and Table 2) in Figure 12 where Z1, Z2, Z3, and Z4 denote the TSC site classifications, and the summary of their definitions is given in Table 5. As a rough conversion, it may be considered that Z1 is equivalent to NEHRP class S_B, Z2 to S_C, Z3 to S_D, and Z4 to S_E. The same correspondence is also valid for our site categorization such that rock, soil, and soft soil refer to Z2, Z3, and Z4, respectively. In this figure, near-field records (r_{cl}<10 km) have been intentionally selected to emphasize those ground motions that are generally of engineering significance. It should be also noted that the calculation of the code-basis spectra for rock sites does not have an influence on the acceleration at zero period. It changes only the length of the constant acceleration plateau (longer for soil and soft-soil site categories). The comparisons of curves reveal that the spectra computed from the recorded accelerations are usually close to regulatory elastic spectra for short periods and lie below the regulatory elastic spectra for longer periods, whereas the estimated response curves generally agree with the computed responses of recorded accelerations at different magnitude, distance, and site categories.

The smoothed and normalized spectra with respect to PGA are further compared with the normalized regulatory elastic spectra as shown in Figure 13 for various site classes and distances. The comparisons for magnitude 7.5 earthquake show that code-basis spectra significantly overestimate the spectral accelerations in the mid- and long-period range (i.e., T>0.7 sec).

COMPARISON WITH 1997 *UBC* DESIGN SPECTRA

The smooth design spectra are next compared with those given in the 1997 *UBC* (ICBO 1997). The comparison for corner periods of design spectra and corresponding shear-wave velocities for each site category is presented in Table 6. In the interest of consistency, only equivalent geological conditions classified according to their shear-

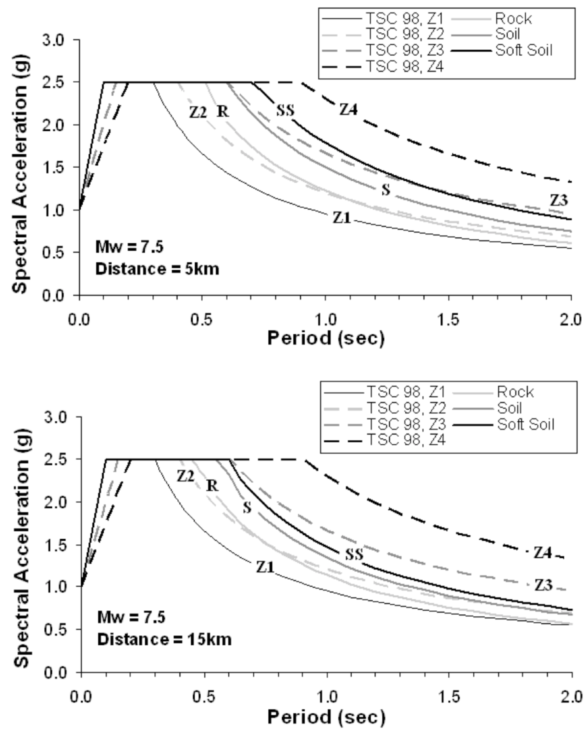

Figure 13. Comparison of 5-percent-damped normalized smooth spectra for magnitude 7.5 and distances of 5 and 15 km with current *Turkish Seismic Code* (1998) at various site categories (SS: soft soil; S: soil; R: rock).

wave velocities by *UBC* are compared with those used in this study. In Figure 14, the normalized 5-percent-damped spectra are compared for various site conditions at 5- and 15-km distances. The normalized comparisons show that there exists considerable overlapping of the possible ranges of spectral shapes for different site categories. The non-normalized proposed smooth spectra are subsequently compared with those of the *UBC* in Figure 15. In this figure, *UBC* spectra display conservatism compared to smooth spectra based on Equation 1. In fact, the values for construction of spectra given in the *UBC* and this study were obtained from different sources, models and site classifications, the generally good agreement between them tends to support estimated corner periods and spectrum shapes for soft soil, soil, and rock site categories as described in Table 4.

UNCERTAINTY IN GROUND MOTION RELATIONS

The uncertainty in ground motion relations, both modeling (uncertainty in the simulation process) and parametric (uncertainty in the parameters of future earthquakes), is a pivotal component of probabilistic hazard analysis for prescribing accuracy and quality of the procedures. The former can be described by the standard error and the bias, whereas the parameters in the second set include the slip distribution, the location of

Table 6. Comparison of corner periods given in the *UBC* (ICBO 1997) and this study at corresponding site categories

SOIL PROFILE TYPE							
		Rock		Soil		Soft Soil	
	Shear Wave Vel. (m/sec)	>700		200–700		<200	
	Distance	T_A	T_B	T_A	T_B	T_A	T_B
This Study	<2 km	0.10	0.51	0.12	0.61	0.14	0.71
	5 km	0.10	0.49	0.12	0.60	0.14	0.71
	10 km	0.09	0.47	0.12	0.58	0.13	0.64
	>15 km	0.09	0.45	0.11	0.54	0.12	0.59
		S_B		S_C		S_D	
	Shear Wave Vel. (m/sec)	760–1500		360–760		180–360	
	Distance	T_O	T_S	T_O	T_S	T_O	T_S
UBC (1997)	<2 km	0.11	0.53	0.15	0.74	0.16	0.78
	5 km	0.11	0.53	0.15	0.74	0.16	0.78
	10 km	0.10	0.48	0.13	0.67	0.14	0.70
	>15 km	0.10	0.40	0.11	0.56	0.12	0.58

hypocenter, slip, and rupture velocity (Somerville 2000). We did not pay attention to parametric uncertainty in this study, only focusing on the modeling uncertainty. In general, ground motion models yield estimates of the probability distribution of ground motion amplitude for a given event. For most ground motion models, including the one presented here, this distribution is assumed to be lognormal and is characterized by a mean and a (logarithmic) standard deviation ($\sigma_{\ln Y}$). The uncertainties causing these standard deviations, partly stemming from the lack and/or poor reliability of the specific supporting data, affect all analytical methods and procedures for the derivation of parameter estimates (Kalkan and Gülkan 2004b). Data exist that show that little reduction in σ may result even when site conditions are well established (Field and Petersen 2000). The attenuation relationships presented in this study cannot, and do not, eliminate these uncertainties. The results we have presented in tabular and graphical form become meaningful only in the context of the error distributions that are associated with each variable. In general, our results have larger deviations from the mean in comparison with, e.g., Boore et al. (1997). This is partly because of the sheer dearth of our data and sparseness of strong-motion recording stations in the national seismic network.

Another commonly used parameter to address the uncertainties in predictive equations is the bias, indicating on average how close the attenuation relation estimates the recorded motions. Figure 16 demonstrates the residuals of natural logarithm of the observed acceleration values produced by Equation 1 with its coefficients given in Table 2 for four different response periods (0.1, 0.3, 0.5, and 1.0 sec). It is shown that differ-

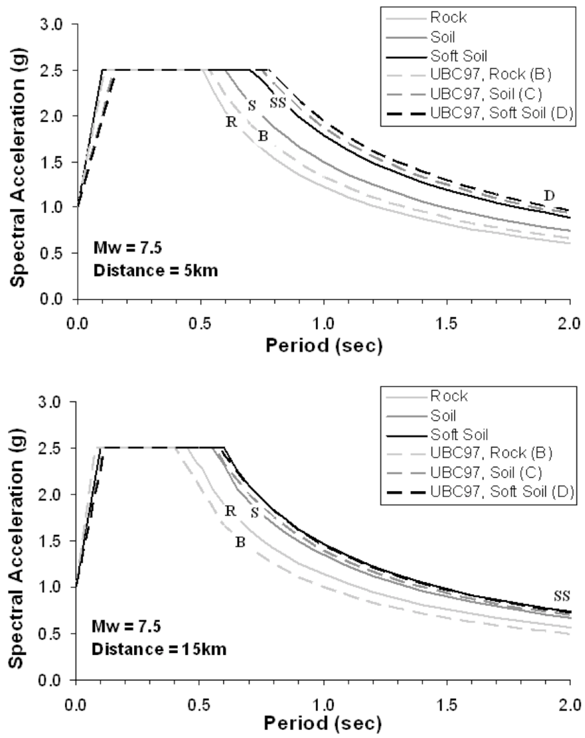

Figure 14. Comparison of 5-percent-damped normalized smooth spectra for magnitude 7.5 and distances of 2 and 10 km with *UBC* (ICBO 1997) design spectra at various site categories (SS: soft soil; S: soil; R: rock).

ences between the mean of residuals for the different site classifications are close to zero. Therefore, there is no significant bias observed in these predictions in the period range of 0 to 2.0 sec.

DISCUSSION

The elastic design spectrum currently used for earthquake-resistant design practice in Turkey is obtained by anchoring a standard smooth shape to effective peak ground acceleration. These shapes are based on broadly described geological conditions, ignoring fault distance or magnitude range dependency on spectral ordinates. In this article, we provide as an alternative hazard-consistent design spectra based on a set of attenuation relationships to estimate peak ground and spectral accelerations. In general, our equations predict lower values at distances closer than 10 km and at magnitudes greater than 7.0 when compared to other common attenuation models. This is consistent with our previous observation regarding attenuation characteristics of national earthquakes (Gülkan and Kalkan 2002). The database for this article has been broadened to enable more representative predictions of ground motion in future earthquakes. Inclusion of a larger number of strong motion seismograms has changed the parameters of the predic-

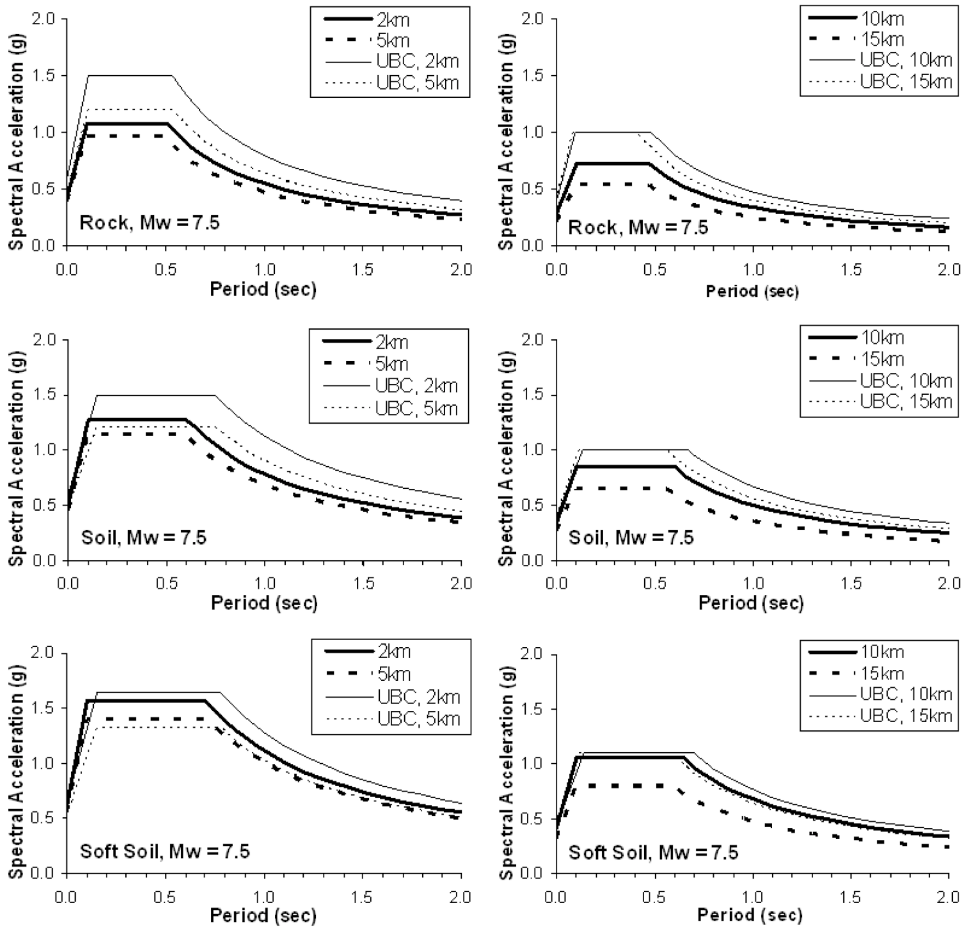

Figure 15. Comparison of smooth spectra for 5 percent of critical damping for rock, soil, and soft-soil site conditions at various distances (*UBC* site classes are S_B, S_C, and S_D corresponding to rock, soil, and soft soil).

tive equation listed in Table 2, but this is a trend that has befallen other ground motion prediction models. Each new earthquake will cause further subtle modifications in those parameters.

We have explored the influence of the site geology on the amplitude of peak ground and spectral accelerations, and compared the site-dependent predictions with equations proposed for Europe and North Western America (NWA). The logarithmic ratios of the soft soil to rock data, and soil to rock data for PGA and spectral accelerations at periods of 0.2, 0.5, 1.0, 1.5, and 2.0 sec are marked on Figure 17. The data points that are comparable to ours come from the predictive model of Ambraseys et al. (1996) for European earthquakes and from Boore et al. (1997), Campbell (1997), Sadigh et al. (1997), and Spudich et al. (1999) for NWA earthquakes. It can be noted that for PGA and short-

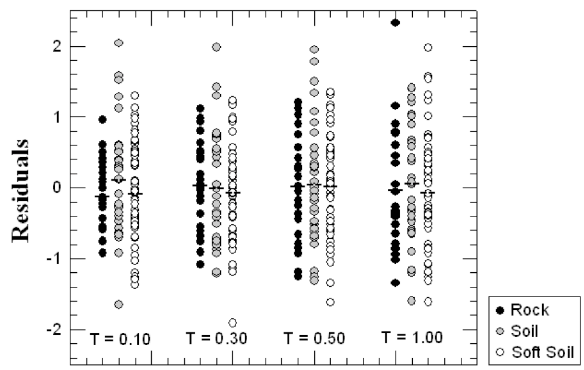

Figure 16. Distribution of residual of the natural logarithm of actual spectral amplitude with respect to estimated values from Equation 1 and Table 2 at periods of 0.1, 0.3, 0.5, and 1.0 sec for three site categories. The horizontal bars denote mean of residuals for each site class.

period (T<0.3 sec) spectral ordinates, the effects of geological conditions on the amplitude of response are in agreement and lie between our model and both European and NWA models. For soil sites, the amplification values of Sadigh et al. (1997) at 0.5 sec are less than our data but dissimilar to the rest that give higher estimates. We also note that Sadigh et al. (1997) show de-amplification on soil sites at short periods up to about 0.3 sec, a feature not found by others or by our study.

It is also noteworthy that we find smaller amplifications at T=0.5 and 1.0 sec compared to NWA and European attenuation models, whereas at long periods our predic-

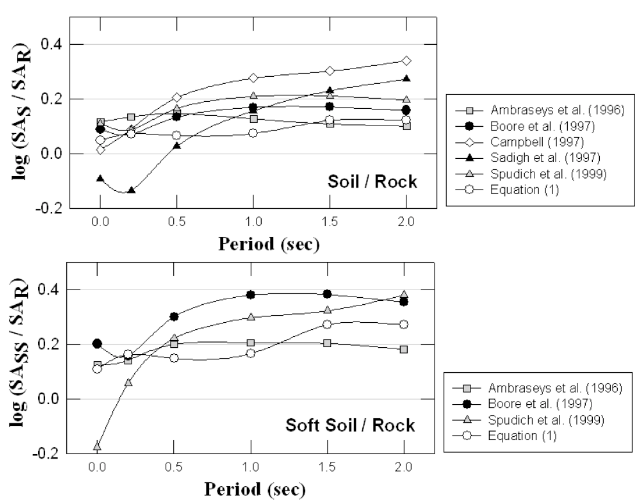

Figure 17. Logarithmic ratio of peak ground and spectral accelerations for soil and soft soil sites to rock motions for magnitude 7.4 and distance of 10 km (SS: soft soil; S: soil; R: rock).

tions are close to the European model for soil amplification and increases for soft soil amplification. However, they still fall below the NWA amplifications. In general, the lack of amplification with respect to high rock-motion amplitudes is directly related to the nonlinear stress-strain behavior of the soil as the bedrock acceleration increases during high-magnitude shaking (Idriss 1990, 1991; Dobry et al. 2000). The results that we have presented in this article seem to advocate this fact partly because of the undue presence of high-magnitude earthquakes in our data set. In fact, many stations in our database are located on soil and soft-soil site geology, and most of them were triggered during the (M_W 7.4) Kocaeli and the (M_W 7.2) Düzce earthquakes, and some of the stations were triggered during both events. Apparent nonlinear soil behavior was suspected to have occurred in the close vicinity of many stations (Bakir et al. 2002, Safak et al. 2000). The saturation of high-amplitude motions at the velocity-sensitive regions of the site response spectra may be attributed to this fact.

The findings showed that the current design spectra reflected by the *Turkish Seismic Code* are conservative for structures. The results in this article provide a framework for improving estimates of site-dependent response spectra for design, site-dependent building code provisions, and predictive maps of strong ground-motion shaking for purposes of earthquake hazard mitigation. A logical extension would be the construction of S_a maps for 0.2 and 1.0 sec as an improvement of the current seismic zones map in Turkey.

The design spectra curves presented in this article are consistent with the expectation of increasing amplification for decreasing soil stiffness for a given acceleration level. The corner periods are also consistent with those from the *UBC* (ICBO 1997), and in no case are they more than 18 percent different than the *UBC* values. Depending on the parameters used to express the quantity of interest in the estimating equation, the physical parameters can serve as proxies for one another, and the vagaries involved in estimating future occurrences of ground motion from past observations are likely to be diminished only when the physics of the phenomena is better understood.

ACKNOWLEDGMENTS

The authors appreciated the help of Mehmet Çelebi at USGS, and Sinan Akkar and Tolga Yilmaz in the Disaster Management Research Center at Middle East Technical University (METU/DMC). Sincere thanks are extended to Ulubey Çeken, Zahide Çolakoglu, and Tülay Ugras at the Earthquake Research Department (ERD) of General Directorate of Disaster Affairs. Most of our data has been supplied originally by ERD. Bogazicçi University's Kandilli Observatory (KOERI) and Istanbul Technical University (ITU) data have also been used in this work.

APPENDIX

Table A1 is a comprehensive description of strong ground motion records of 57 earthquakes that occurred between 1976 and 2003 in Turkey. This is an expanded and updated version of the previously compiled database by Gülkan and Kalkan (2002), which included records of 19 earthquakes occurring in Turkey between 1976 and 1999.

Table A1. Database of strong motion records in Turkey (August 1976–July 2003)

Data No	Date (dd.mm.yy)	Event	M_W	r_{cl} (km)	Station Code	Location	Owner *	Station Coordinates	Local Geology	V_S (m/s) **	Information Source ***	Peak Ground Acc. (g) NS	EW	Ver.
1	19.08.1976	DENİZLİ	5.3	15.1	DNZ	Denizli: Bayındırlık ve İsk. Müd.	ERD	37.8120N - 29.1140E	Soil	-	AMB	0.349	0.290	0.173
2	05.10.1977	ÇERKEŞ	5.4	62.1	CER	Çerkeş: Meteoroloji İst.	ERD	40.8140N - 32.8830E	Soft Soil	-	ERD	0.036	0.039	0.016
3	16.12.1977	İZMİR	5.5	1.2	IZM	İzmir: Meteoroloji İst.	ERD	38.4390N - 27.1670E	Soft Soil	-	ERD	0.391	0.125	0.094
4	11.04.1979	MURADİYE	4.9	19.0	MUR	Muradiye: Meteoroloji İst.	ERD	38.9900N - 43.7680E	Rock	-	ERD	0.046	0.045	0.025
5	28.05.1979	BUCAK	5.8	150.0	BCK	Bucak: Kandilli Gozlem Evi	ERD	37.4610N - 30.5890E	Rock	-	ERD	0.024	0.021	0.041
6	18.07.1979	DURSUNBEY	5.3	10.3	DUR	Dursunbey: Kandilli Gözlem İst.	ERD	39.6700N - 28.5300E	Rock	-	ERD	0.232	0.288	0.200
7	30.06.1981	HATAY	4.7	24.7	HTY	Hatay: Bayındırlık ve İskan Müd.	ERD	36.2130N - 36.1600E	Soil	-	ERD	0.154	0.136	0.144
8	05.07.1983	BİGA	6.1	57.7	EDC	Edincik: Kandilli Gözlem İst.	ERD	40.3600N - 27.8900E	Rock	-	AMB2000	0.053	0.047	0.032
9	05.07.1983	BİGA	6.1	48.7	GNN	Gönen: Meteoroloji İst.	ERD	40.0800N - 27.6800E	Soft Soil	-	ERD	0.050	0.048	0.038
10	05.07.1983	BİGA	6.1	75.0	TKR	Tekirdağ: Bayındırlık ve İsk. Müd.	ERD	40.9790N - 27.5150E	Rock	-	PEER, ERD	0.030	0.035	0.017
11	30.10.1983	HORASAN-NARMAN	6.5	25.0	HRS	Horasan: Meteoroloji İst.	ERD	40.0430N - 42.1730E	Soft Soil	-	ERD	0.150	0.173	0.088
12	30.10.1983	HORASAN-NARMAN	6.5	92.5	ERZ	Erzurum: Bayındırlık ve İsk. Müd.	ERD	39.9030N - 41.2620E	Soft Soil	-	ERD	0.035	0.025	0.032
13	29.03.1984	BALIKESİR	4.5	2.4	BLK	Balıkesir: Huzur Evi	ERD	39.6500N - 27.8600E	Soft Soil	-	ERD	0.224	0.129	0.297
14	17.06.1984	FOÇA	5.0	98.0	FOC	Foça: Gümrük Müd.	ERD	38.6400N - 26.7700E	Rock	-	ERD	0.024	0.023	0.024
15	12.08.1985	KİĞI	4.9	80.8	KIG	Kiğı: Meteoroloji İst.	ERD	39.3400N - 40.2800E	Soil	-	ERD	0.163	0.089	0.043
16	06.12.1985	KÖYCEĞİZ	4.6	14.4	KOY	Köyceğiz: Meteoroloji İst.	ERD	36.9670N - 28.6808E	Soft Soil	-	ERD	0.103	0.114	0.069
17	05.05.1986	MALATYA	6.0	29.6	GOL	Gölbaşı: Meteoroloji Müd.	ERD	37.7810N - 37.6410E	Rock	-	ERD	0.115	0.076	0.039
18	06.06.1986	SÜRGÜ (MALATYA)	6.0	34.7	GOL	Gölbaşı: Meteoroloji Müd.	ERD	37.7810N - 37.6410E	Rock	-	ERD	0.069	0.034	0.018
19	06.06.1986	SÜRGÜ (MALATYA)	6.0	53.6	MLT	Malatya: Bay. İsk. Müd.	ERD	38.3500N - 38.3460E	Soil	-	ERD	0.023	0.025	0.026
20	20.04.1988	MURADİYE	5.0	37.3	MUR	Muradiye: Meteoroloji İst.	ERD	38.9900N - 43.7680E	Rock	-	ERD	0.050	0.051	0.021
21	12.02.1991	İSTANBUL	4.8	38.5	IST	İstanbul: Kandilli Gözlem Evi	ERD	41.0800N - 29.0900E	Rock	-	ERD	0.026	0.018	0.010
22	13.03.1992	ERZİNCAN	6.9	5.0	ERC	Erzincan: Bayındırlık ve İsk. Müd.	ERD	39.7430N - 39.5120E	Soil	-	ERD	0.405	0.471	0.239
23	13.03.1992	ERZİNCAN	6.9	65.0	REF	Refahiye: Kaymakamlık Binası	ERD	39.9010N - 38.7690E	Soft Soil	-	ERD	0.067	0.086	0.032
24	06.11.1992	SİVRİHİSAR	6.1	41.0	KUS	Kuşadası: Meteoroloji İst.	ERD	37.8610N - 27.2660E	Soft Soil	-	ERD	0.084	0.072	0.062
25	03.01.1994	ISLAHİYE	5.0	67.7	ISL	Islahiye: Meteoroloji İst.	ERD	37.0500N - 36.6000E	Soil	-	ERD	0.021	0.019	0.019
26	24.05.1994	GİRİT	5.0	20.1	FOC	Foça: Gümrük Müd.	ERD	38.6400N - 26.7700E	Rock	-	ERD	0.036	0.050	0.030
27	13.11.1994	KÖYCEĞİZ	5.2	17.4	KOY	Köyceğiz: Meteoroloji İst.	ERD	36.9670N - 28.6880E	Soft Soil	-	ERD	0.073	0.097	0.058
28	29.01.1995	TERCAN	4.8	55.5	TER	Tercan: Meteoroloji İst.	ERD	39.7800N - 40.3940E	Soil	-	ERD	0.045	0.049	0.025
29	26.02.1995	VAN	4.7	12.6	VAN	Van: Bayındırlık ve İskan Müd.	ERD	38.5040N - 43.4060E	Soft Soil	-	ERD	0.028	0.016	0.016
30	01.10.1995	DİNAR	6.4	3.0	DIN	Dinar: Meteoroloji İst.	ERD	38.0600N - 30.1550E	Soft Soil	-	NEI, AND	0.282	0.330	0.151
31	01.10.1995	DİNAR	6.4	39.6	CRD	Çardak: Sağlık Ocağı	ERD	37.8240N - 29.6680E	Soil	-	AND	0.065	0.061	0.098
32	02.04.1996	KUŞADASI	4.9	55.7	KUS	Kuşadası: Meteoroloji İst.	ERD	37.8610N - 27.2660E	Soft Soil	-	ERD	0.021	0.033	0.022
33	14.08.1996	MERZİFON	5.4	21.7	MRZ	Merzifon: Meteoroloji İst.	ERD	40.8800N - 35.4590E	Soft Soil	-	NEI,ERD	0.033	0.102	0.029
34	21.01.1997	BULDAN	4.8	11.3	BLD	Buldan: Kaymakamlık Binası	ERD	38.0450N - 28.8330E	Soil	-	ERD	0.039	0.024	0.028
35	22.01.1997	HATAY	5.5	9.0	HTY	Hatay: Bayındırlık ve İskan Müd.	ERD	36.2130N - 36.1600E	Soil	-	NEI, ERD	0.136	0.150	0.089
36	22.01.1997	HATAY	5.5	110.0	ISL	Islahiye: Meteorologji İst.	ERD	37.0500N - 36.6000E	Soil	-	ERD	0.028	0.030	0.023
37	28.02.1997	MERZİFON	4.7	26.0	MRZ	Merzifon: Meteoroloji İst.	ERD	40.8800N - 35.4590E	Soft Soil	-	ERD	0.015	0.016	0.015
38	03.11.1997	MALAZGİRT	4.9	47.0	MLZ	Malazgirt: Meteoroloji İst.	ERD	39.1700N - 42.5400E	Soft Soil	-	ERD	0.018	0.018	0.011
39	04.04.1998	DİNAR	4.6	13.4	DIN	Dinar: Meteoroloji İst.	ERD	38.0600N - 30.1550E	Soft Soil	-	ERD	0.135	0.131	0.028

Table A1. (cont.). Database of strong motion records in Turkey (August 1976–July 2003)

Data No	Date (dd.mm.yy)	Event	M_W	r_{cl} (km)	Station Code	Location	Owner *	Station Coordinates	Local Geology	V_S (m/s) **	Information Source ***	Peak Ground Acc. (g) NS	EW	Ver.
40	04.04.1998	DİNAR	4.6	48.0	CRD	Çardak: Sağlık Ocağı	ERD	37.8240N - 29.6680E	Soil	-	ERD	0.028	0.024	0.019
41	27.06.1998	ADANA-CEYHAN	6.3	80.1	MRS	Mersin: Meteoroloji İst.	ERD	36.8300N - 34.6500E	Soft Soil	-	NEI	0.119	0.132	0.022
42	27.06.1998	ADANA-CEYHAN	6.3	28.0	CYH	Ceyhan: PTT Müd.	ERD	37.0240N - 35.8090E	Soft Soil	-	ERD, ADA	0.223	0.274	0.086
43	27.06.1998	ADANA-CEYHAN	6.3	95.8	ISL	Islahiye: Meteoroloji İst.	ERD	37.0500N - 36.6000E	Soil	-	ERD	0.021	0.018	0.014
44	27.06.1998	ADANA-CEYHAN	6.3	58.8	ISK	İskenderun: Meteoroloji İst.	ERD	36.6300N - 36.1500E	Soil	-	ERD	0.015	0.015	0.012
45	27.06.1998	ADANA-CEYHAN	6.3	89.0	HTY	Hatay: Bayındırlık ve İskan Müd.	ERD	36.2130N - 36.1600E	Soil	-	ERD	0.027	0.026	0.012
46	27.06.1998	ADANA-CEYHAN	6.3	36.0	KRT	Karatas: Meteoroloji Ist.	ERD	36.5610N - 35.3670E	Rock	-	ERD	0.029	0.033	0.020
47	09.07.1998	BORNOVA	5.1	63.0	BRN	Bornova: Ziraat Fakultesi	ERD	38.4550N - 27.2290E	Soft Soil	-	ERD	0.027	0.013	0.006
48	17.08.1999	KOCAELİ	7.4	66.6	BRS	Bursa: Sivil Sav. Müd.	ERD	40.1830N - 29.1310E	Soft Soil	-	PEER, ERD, RATH	0.054	0.046	0.026
49	17.08.1999	KOCAELİ	7.4	76.1	CEK	Çekmece: Nükleer Santral Bn.	ERD	40.9700N - 28.7000E	Soil	350	PEER, RATH	0.118	0.090	0.050
50	17.08.1999	KOCAELİ	7.4	11.0	DZC	Düzce: Meteoroloji İst.	ERD	40.8440N - 31.1490E	Soil	275	PEER, ERD, RATH	0.315	0.374	0.480
51	17.08.1999	KOCAELİ	7.4	116.0	ERG	Ereğli: Kaymakamlık Bn.	ERD	40.9800N - 27.7900E	Soil	-	ERD	0.090	0.101	0.057
52	17.08.1999	KOCAELİ	7.4	15.0	GBZ	Gebze: Tübitak Marmara Araş. Mer.	ERD	40.8200N - 29.4400E	Rock	750	PEER, ERD, RATH	0.265	0.141	0.198
53	17.08.1999	KOCAELİ	7.4	30.0	IZN	İznik: Kaymakamlık Binası	ERD	40.4300N - 29.72 0E	Soft Soil	180-190	PEER, ERD, RATH	0.265	0.123	0.082
54	17.08.1999	KOCAELİ	7.4	49.0	IST	İstanbul: Bayındırlık ve İskan Müd.	ERD	41.0580N - 29.0130E	Rock	-	ERD	0.061	0.043	0.036
55	17.08.1999	KOCAELİ	7.4	3.2	SKR	Sakarya: Bayındırlık ve İskan Müd.	ERD	40.7370N - 30.3840E	Soil	470	PEER, ERD, AKK, RATH	N/A	0.407	0.259
56	17.08.1999	KOCAELİ	7.4	4.3	IZT	İzmit: Meteoroloji İst.	ERD	40.7900N - 29.9600E	Rock	800	PEER, ERD, RATH	0.171	0.225	0.146
57	17.08.1999	KOCAELİ	7.4	32.0	GYN	Göynük: Devlet Hastanesi	ERD	40.3960N - 30.7830E	Rock	-	PEER, ERD, RATH	0.138	0.118	0.130
58	17.08.1999	KOCAELİ	7.4	144.6	KUT	Kütahya: Sivil Savunma Müd.	ERD	39.4190N - 29.9970E	Soil	-	PEER, ERD	0.050	0.060	0.023
59	17.08.1999	KOCAELİ	7.4	183.4	BLK	Balıkesir: Huzur Evi	ERD	39.6500N - 27.8600E	Soft Soil	-	PEER, ERD	0.018	0.018	0.008
60	17.08.1999	KOCAELİ	7.4	250.0	CNK	Çanakkale: Meteoroloji İst.	ERD	40.1420N - 26.4020E	Soft Soil	-	SUC, ERD	0.025	0.029	0.008
61	17.08.1999	KOCAELİ	7.4	67.5	ATK	Ataköy	ITU	40.9890N - 28.8490E	Soft Soil	-	PEER	0.102	0.168	0.068
62	17.08.1999	KOCAELİ	7.4	62.3	MCD	Mecidiyeköy	ITU	41.0650N - 28.9970E	Rock	-	PEER	0.054	0.070	0.037
63	17.08.1999	KOCAELİ	7.4	63.9	MSK	Maslak	ITU	41.1040N - 29.0190E	Rock	-	PEER	0.054	0.038	0.031
64	17.08.1999	KOCAELİ	7.4	63.1	ZYT	Zeytinburnu	ITU	40.9860N - 28.9080E	Soft Soil	-	PEER	0.120	0.109	0.051
65	17.08.1999	KOCAELİ	7.4	17.0	ARC	Darıca: Arçelik Arge Bn.	KOERI	40.8236N - 29.3607E	Soil	360-500	COS, USGS, PEER, RATH	0.211	0.134	0.083
66	17.08.1999	KOCAELİ	7.4	78.9	ATS	Ambarlı: Termik Santral	KOERI	40.9809N - 28.6926E	Soft Soil	175	COS, USGS, PEER, RATH	0.253	0.186	0.080
67	17.08.1999	KOCAELİ	7.4	136.3	BTS	M. Ereğlisi: Botaş Gas Terminali	KOERI	40.9919N - 27.9795E	Soil	-	COS, USGS, PEER	0.099	0.087	0.024
68	17.08.1999	KOCAELİ	7.4	69.3	DHM	Yeşilköy: Havalimanı	KOERI	40.9823N - 28.8199E	Soil	-	COS, USGS, PEER	0.090	0.084	0.055
69	17.08.1999	KOCAELİ	7.4	3.3	YPT	Yarımca: Petkim Tesisleri	KOERI	40.7639N - 29.7620E	Soil	300	COS, USGS, AKK, RATH	0.230	0.322	0.241
70	17.08.1999	KOCAELİ	7.4	63.0	FAT	Fatih: Fatih Türbesi	KOERI	41.0196N - 28.9500E	Soft Soil	-	COS, USGS, PEER	0.189	0.162	0.132
71	17.08.1999	KOCAELİ	7.4	60.7	YKP	4. Levent: Yapı Kredi Plaza	KOERI	41.0811N - 20.0111E	Rock	-	COSMOS, PEER	0.041	0.036	0.027
72	17.08.1999	KOCAELİ	7.4	43.0	HAS	Heybeliada: Sanatoryum	KOERI	40.8688N - 29.0875E	Rock	-	COSMOS	0.057	0.110	0.143
73	17.08.1999	KOCAELİ	7.4	62.7	BUR	Bursa: Tofaş Fab.	KOERI	40.2605N - 29.0680E	Soft Soil	-	COS, USGS, PEER	0.101	0.100	0.048
74	11.11.1999	SAPANCA-ADAPAZARI	5.7	17.5	SKR	Sakarya: Bayındırlık ve İskan Müd.	ERD	40.7370N - 30.3840E	Soil	470	ERD, RATH	0.207	0.345	0.133
75	12.11.1999	DÜZCE	7.2	20.4	BOL	Bolu: Bayındırlık ve İskan Müd.	ERD	40.7470N - 31.6100E	Soil	290	PEER, ERD, AKK, RATH	0.740	0.806	0.200
76	12.11.1999	DÜZCE	7.2	8.2	DZC	Düzce: Meteoroloji İst.	ERD	40.8440N - 31.1490E	Soil	275	PEER, ERD, AKK, RATH	0.408	0.514	0.340
77	12.11.1999	DÜZCE	7.2	56.4	GYN	Göynük: Devlet Hastanesi	ERD	40.3960N - 30.7830E	Rock	-	PEER, ERD	0.028	0.025	0.025
78	12.11.1999	DÜZCE	7.2	129.8	IZN	İznik: Kaymakamlık Binası	ERD	40.4300N - 29.7200E	Soft Soil	180-190	PEER, RATH	0.022	0.021	0.010
79	12.11.1999	DÜZCE	7.2	95.0	IZT	İzmit: Meteoroloji İst.	ERD	40.7900N - 29.9600E	Rock	800	PEER, ERD, RATH	0.022	0.024	0.022
80	12.11.1999	DÜZCE	7.2	30.9	MDR	Mudurnu: Kaymakamlık Binası	ERD	40.4690N - 31.2100E	Soft Soil	-	ERD	0.121	0.058	0.063
81	12.11.1999	DÜZCE	7.2	169.5	KUT	Kütahya: Sivil Savunma Müd.	ERD	39.4190N - 29.9970E	Soil	-	PEER, ERD	0.017	0.021	0.009
82	12.11.1999	DÜZCE	7.2	49.9	SKR	Sakarya: Bayındırlık ve İskan Müd.	ERD	40.7370N - 30.3840E	Soil	470	PEER, ERD, RATH	0.017	0.025	0.018
83	12.11.1999	DÜZCE	7.2	193.3	ATS	Ambarlı: Termik Santral	KOERI	40.9809N - 28.6926E	Soft Soil	175	COS, USGS, PEER, RATH	0.038	0.027	0.008

Table A1. (cont.). Database of strong motion records in Turkey (August 1976–July 2003)

Data No	Date (dd.mm.yy)	Event	M_W	r_{el} (km)	Station Code	Location	Owner *	Station Coordinates	Local Geology	V_S (m/s) **	Information Source ***	Peak Ground Acc. (g) NS	EW	Ver.
84	12.11.1999	DÜZCE	7.2	179.0	HAS	Heybeliada: Sanatoryum	KOERI	40.8688N - 29.0875E	Rock	-	COS	0.024	0.028	0.016
85	12.11.1999	DÜZCE	7.2	172.5	FAT	Fatih: Fatih Türbesi	KOERI	41.0196N - 28.9500E	Soft Soil	-	COS, USGS, PEER	0.036	0.025	0.008
86	12.11.1999	DÜZCE	7.2	101.7	YPT	Yarımca: Petkim Tesisleri	KOERI	40.7639N - 29.7620E	Soil	300	COS, USGS, PEER, RATH	0.018	0.016	0.014
87	06.06.2000	ÇANKIRI-ORTA	6.1	30.0	CER	Çerkeş: Meteoroloji İst.	ERD	40.8140N - 32.8830E	Soft Soil	-	ERD, DEM1	0.062	0.063	0.040
88	23.08.2000	HENDEK-AKYAZI	5.1	7.5	AKY	Akyazı: Orman İşletme Müd.	ERD	40.6700N - 30.6220E	Soft Soil	-	USGS, DEM2	0.079	0.097	0.030
89	23.08.2000	HENDEK-AKYAZI	5.1	88.1	IZN	İznik: Kaymakamlık Binası	ERD	40.4300N - 29.7200E	Soft Soil	180-190	USGS, DEM2, RATH	0.022	0.016	0.008
90	23.08.2000	HENDEK-AKYAZI	5.1	41.2	DZC	Düzce: Meteoroloji İst.	ERD	40.8440N - 31.1490E	Soil	275	USGS, DEM2, RATH	0.023	0.018	0.009
91	23.08.2000	HENDEK-AKYAZI	5.1	28.2	SKR	Sakarya: Bayındırlık ve İskan Müd.	ERD	40.7370N - 30.3840E	Soil	470	USGS, DEM2, RATH	0.021	0.027	0.016
92	04.10.2000	DENIZLİ	4.7	12.7	DNZ	Denizli: Bayındırlık ve İskan Müd.	ERD	37.8120N - 29.1140E	Soil	-	ERD	0.049	0.066	0.049
93	15.11.2000	TATVAN-VAN	5.5	200.0	VAN	Van: Bayındırlık ve İskan Müd.	ERD	38.5040N - 43.4060E	Soft Soil	-	ERD	0.013	0.012	0.007
94	10.07.2001	ERZURUM-PASİNLER	5.4	31.7	ERZ	Erzurum: Bayındırlık ve İskan Müd.	ERD	39.9030N - 41.2620E	Soft Soil	-	ERD	0.020	0.022	0.027
95	26.08.2001	YIĞILCA-DÜZCE	5.4	22.3	BOL	Bolu: Bayındırlık ve İskan Müd.	ERD	40.7470N - 31.6100E	Soil	290	ERD, RATH	0.189	0.132	0.044
96	02.12.2001	VAN	4.5	15.9	VAN	Van: Bayındırlık ve İskan Müd.	ERD	38.5040N - 43.4060E	Soft Soil	-	ERD	0.030	0.025	0.034
97	03.02.2002	SULTANDAĞI-ÇAY	6.5	66.3	AFY	Afyon: Bayındırlık ve İskan Müd.	ERD	38.7920N - 30.5610E	Soft Soil	-	ERD	0.114	0.094	0.036
98	03.02.2002	SULTANDAĞI-ÇAY	6.5	143.0	KUT	Kütahya: Sivil Savunma Müd.	ERD	39.4190N - 29.9970E	Soil	-	GUL	0.023	0.021	0.014
99	03.04.2002	BURDUR	4.2	12.5	BRD	Burdur: Bayındırlık ve İskan Müd.	ERD	37.7040N - 30.2210E	Soil	-	AND	0.029	0.021	0.031
100	14.12.2002	ANDIRIN-K. MARAŞ	4.8	16.0	AND	Andırın: Tufan Paşa İlkokulu	ERD	37.5800N - 36.3400E	Soil	-	ERD	0.077	0.050	0.032
101	10.03.2003	AKYAZI	4.0	6.6	AKY	Akyazı: Orman İşletme Müd.	ERD	40.6700N - 30.6220E	Soft Soil	-	ERD	0.028	0.035	0.012
102	10.04.2003	URLA-IZMIR	5.8	48.0	BRN	Bornova: 9 Eylül Üniv. Ziraat Fak.	ERD	38.4550N - 27.2290E	Soft Soil	-	ERD	0.079	0.037	0.017
103	01.05.2003	BINGOL	6.4	6.1	BNG	Bingol: Bayindirlik ve Iskan Mud.	ERD	38.8860N - 40.5010E	Soft Soil	-	ERD, USGS	0.544	0.277	0.472
104	21.05.2003	DUZCE	4.7	19.0	DZC	Düzce: Meteoroloji İst.	ERD	40.8440N - 31.1490E	Soil	275	ERD, RATH	0.018	0.032	0.017
105	09.06.2003	BANDIRMA	4.0	14.2	BND	Bandırma: Bölge Trafik Den. Am.	ERD	40.3410N - 27.9420E	Soil	-	ERD	0.036	0.023	0.015
106	06.07.2003	SAROS	5.3	35.0	CNK	Canakkale: Meteoroloji İst.	ERD	40.1420N - 26.4020E	Soft Soil	-	ERD	0.026	0.016	0.009
107	23.07.2003	BULDAN-DENIZLI-1	5.5	46.1	DNZ	Denizli: Bayındırlık ve İsk. Müd.	ERD	37.8120N - 29.1140E	Soil	-	ERD, DEM3	0.022	0.046	0.020
108	23.07.2003	BULDAN-DENIZLI-1	5.5	27.4	DATI	Denizli-Saraykoy: Jeotermal Isl.Mud.	ERD	37.9320N - 28.9230E	Soft Soil	-	ERD, DEM3	0.090	0.123	0.061
109	26/07/2003	BULDAN-DENIZLI-2	5.3	20.2	DATI	Denizli-Saraykoy: Jeotermal Isl.Mud.	ERD	37.9320N - 28.9230E	Soft Soil	-	ERD, DEM3	0.048	0.034	0.036
110	26/07/2003	BULDAN-DENIZLI-3	5.7	38.5	DNZ	Denizli: Bayındırlık ve İsk. Müd.	ERD	37.8120N - 29.1140E	Soil	-	ERD, DEM3	0.024	0.026	0.022
111	26/07/2003	BULDAN-DENIZLI-3	5.7	20.0	DATI	Denizli-Saraykoy: Jeotermal Isl.Mud.	ERD	37.9320N - 28.9230E	Soft Soil	-	ERD, DEM3	0.108	0.120	0.154
112	26/07/2003	BULDAN-DENIZLI-4	5.2	22.1	DATI	Denizli-Saraykoy: Jeotermal Isl.Mud.	ERD	37.9320N - 28.9230E	Soft Soil	-	ERD, DEM3	0.014	0.017	0.010

* Data source: ERD-General Directorate of Disaster Affairs, Earthquake Research Dept. (www.deprem.gov.tr); KOERI-Bogazici University, Kandilli Observatory and Earthquake Research Institute, (www.koeri.boun.edu.tr); ITU-Istanbul Technical University, (www.ins.itu.edu.tr).

** Rathje et al. (2003)

*** Information sources: ADA-Adalier et al.(2000); AKK-Akkar et al. (2002); AMB-Ambraseys et al. (1988); AMB2000-Ambraseys et al. (2000); AND-Anderson et al. (2001); COS-Cosmos, (http://db.cosmos-eq.org); DEM1-Demirtas et al. (2000a); DEM2-Demirtas et al. (2000b); DEM3-Demirtas et al. (2003); GUL-Gülkan et al. (2002a); NEI-CNSS Catalogue, U.S. Council of National Seismic System, (http://quake.geo.berkeley.edu/cnss/catalog-search.html); PEER-Pacific Earthquake Engineering Research Ctr., (http://peer.berkeley.edu/smcat); RATH-Rathje et al. (2003); SUC-Sucuoglu et al. (2001); USGS-Celebi et al. (2001).

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